



Overview of MSFC's Applied Fluid Dynamics Analysis Group Activities

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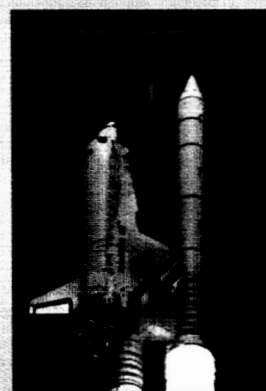
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Overview



- **Introduction**
 - Status of programs at MSFC
 - Fluid Mechanics at MSFC
- **Relevant Fluid Dynamics Activities at MSFC**
 - Combustion devices
 - Turbomachinery
 - Nozzles
- **Shuttle Return to Flight**
 - SRB Boost Separation Motor
 - External Tank redesign
 - Fuel Feedline Flowliner
 - On-pad debris transport
- **Concluding Remarks**



*CFD on Space Transportation
Systems Technology*



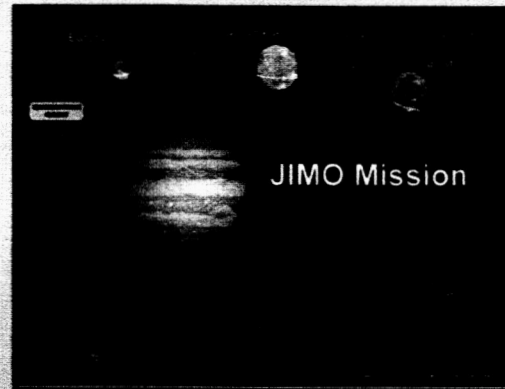
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Status of programs at MSFC - Prometheus



- **Prometheus/JIMO (Jupiter Icy Moon Orbiter)**
 - Project lead by JPL
 - Current in a black-out period due to RFP
 - Develop nuclear-electronic propulsion systems to provide greater energy for science on-site
 - JIMO is a nuclear electric pathfinder vehicle
 - Utilize a nuclear reactor to heat some sort of fluid
 - Fluid used to generate electricity (Brayton cycle, Sterling cycle, etc.)
 - Electric thrusters provide thrust for delta-V
 - Excess power is radiated into space
 - Launch 2011 - 2015, 5-6 year transit to Jupiter
 - Within Prometheus there are also studies for other, nuclear based propulsion concept (i.e., nuclear thermal)



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Status of programs at MSFC - Code T



- **Office of Exploration Systems created to implement the Presidents vision for human space exploration**
 - "returning to the Moon"
 - Code T
- **Major Milestones**
 - 2008: Initial flight test of CEV
 - 2008: Launch first lunar robotic orbiter
 - 2011 First Unmanned CEV flight
 - 2014: First crewed CEV flight
 - 2015: Jupiter Icy Moon Orbiter (JIMO)/Prometheus
 - 2015-2020: First human mission to the Moon
- **HQ centric program, getting engineering support from field centers**
- **A "mission pull" initiative**
 - Technology only if the mission needs it

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Status of programs at MSFC - Code T



- **Conducting studies to aid in the establishment of requirements**
- **Going through the process of reviewing projects that it inherited for relevance to Exploration System needs**
 - Relevance review has resulted in cancellation of several former NGLT projects
 - Redirection of others
 - There will be some low level, very focused near term technology activities
- **Code will have to live with the same metrics as other programs**
 - Support universities, small businesses, etc.
- **SBIR program topics being restructured in line with the initiative and consistent with the "mission-pull" concept**
- **Centennial challenges could be the source of very interesting and spirited competitions**
 - Allows NASA to award prize money to individuals/teams that are first in achieving certain technology/capability goals

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Status of programs at MSFC - Shuttle RTF



- **NASA is being very thorough in its return to flight (RTF) activities**
 - It is implementing the CAIB recommendations and beyond
 - Aiming for RTF in March of 05
- **You get relatively recent RTF information on the web**
 - <http://www.nasa.gov/news/highlights/returntoflight.html>
- **RTF activities are impacting all the code M and code R centers**
- **Major activities being worked (not all inclusive)**
 - Redesigning the ET to eliminate all sources of debris
 - Hardening the shuttle to be more tolerant of debris
 - Improving the orbiter's ability to re-enter safely with minor wing damage
 - TPS on-orbit inspection and repair capability
 - Developing a better RCC properties database
 - Developing a physics based, disciplined debris assessment process
 - Redesign solid rocket booster bolt catcher
 - Improving the film system for improved monitoring of launches (ground and on vehicle)
 - Has established an independent engineering technical authority
 - Reorganized to allow for more effective integration of the shuttle elements
- **All activities being performed with extensive testing and analysis support**

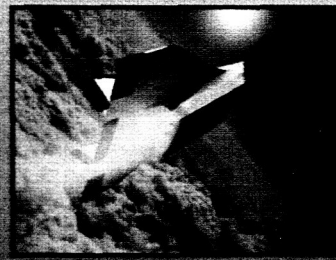
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Introduction



- **High-fidelity fluids design & analysis expertise at MSFC focused in the space transportation directorate**
 - CFD (TD64), induced environments (TD63), cold flow testing (TD62, TD63, TD74), and functional design (TD61)
- **Fluid dynamics expertise a core competency at MSFC**
- **Support focused in two broad areas**
 - Space Shuttle propulsion (Shuttle return to flight)
 - SRB office, ET office, and Shuttle Integration Office
 - Next Generation Launch Technologies
 - Projects/tasks that survive Office of Exploration Systems (Code T) Relevance Review



Introduction: Role of Fluid Mechanics Expertise



- **Fluid mechanics applications at MSFC focused on improving the safety, reliability, & cost of space transportation systems**
- **We define geometry, quantify environments, and predict performance**
 - Incident investigation support (analysis and test)
 - Environments and performance definition (analysis and test)
 - Develop advanced hardware concepts and designs (analysis and test)
- **We support the programs in meeting their goals**
 - Assist the programs in being "smart buyers"
 - Provide innovative technical solutions
- **We work with external partners who possess key capabilities**
 - Other NASA centers, other government agencies, industry, academia



Introduction: CFD Goals



- **Provide personnel with the tools to succeed**
 - Maintain and enhance civil service personnel capabilities
 - Provide challenging work, hands-on experience, training
 - Continuously improve analysis techniques, computing resources, and test facilities, reduce cost/analysis
- **Acquire/develop capability to perform broad, CFD-based parametric design concept studies**
 - Spend more time engineering, less time "CFDing"
 - More efficient use of available computing resources
 - Requires automation in all phases: grid generation, flow solver, post-processing
- **Expand range of CFD applicability**
 - Improved models, combustion, transient processes, relative motion, cavitation, multi-component, multidisciplinary,
 - Greater efficiency and robustness in flow solvers



CFD Software/Hardware in Use at MSFC



- **Grid generation**
 - Gridgen, Solid Mesh, Corgrid, CFD-Geom, CORGRID
- **Post Processing**
 - Fieldview, Ensign, Flowshow, Animator, Autoplot
- **Flow Solvers**
 - FDNS, LOCI-Chem, Corsair, Phantom, Overflow, UNIC
- **Computer Hardware**
 - Access to NASA-Ames SGI based compute clusters (512p & 1024p)
 - Local PC-based clusters and SGI systems
 - Access to local Army compute clusters

Computers	processors	processor speed	ram
Nexus	16	250 MHz, R10k	8.5 GB
Korben	8	300 MHz, R12k	4 GB
Neo	16	500 MHz, R14k	16 GB
Hydra	36	600 Mhz - 933 Mhz PIII	10 GB
Chimaera	200	1500 MHz, Athlon MP	100 GB
Cerberus	336	2100 MHz, AMD 2600	689 GB
Tyrell	32	250 MHz, R10k	32 GB
Desktops	2	400 MHz, R12k	.5 - 2 GB
VMCS	32	600 MHz R14KA	32 GB
VMFS	16	300 MHz, R12k	8 GB



Combustion Devices



- **Technology need**

- Contemporary rocket engine combustion devices similar to 1960s-1970s designs
- Longer life (robust), higher T/W designs required
 - Experimental demonstration of design robustness/life is cost prohibitive
- Application of CFD in design of combustion devices hampered by real limitations
 - Inadequate accuracy (lack of physical modeling)
 - Inadequate turn-around time
 - Inadequate validation and verification where required physics are included in the CFD tools
- Current focus at MSFC is in rocket chamber combustion
 - High pressure, all-speed, reacting flows

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Combustion Devices - The Challenge



- We must support programs with the current, limited capability for injector design
- Concurrently, CFD simulation capability improvements must be made in at least 3 areas
 - Fidelity-the ability to model the key details of the physics and geometry
 - Robustness-solution turnaround must be sufficient to cover a large parametric space of independent design variables and operating conditions
 - Accuracy (demonstrated)-we must be able to quantify accuracy; both current and threshold level for design

**At MSFC, we must
maintain 2 parallel thrusts**

Program Support

Technology Development

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Key Concept--Simulation Readiness Level

Simulation Readiness Level (SRL) = (f,r,a)

Level	Fidelity	Robustness	Accuracy
0	Extremely simple physics, boundary conditions and geometry	Have not completed any simulations	Not evaluated other than historical quality of simulation tool
1	Reasonably precise geometry and boundary conditions, extremely simple physics	Have completed some simulations	Qualitative agreement with existing results of related problems
2	Reasonably precise physics with extremely simple boundary conditions and geometry	Simulations with proven convergence and conservation	Quantitative agreement with existing results of related problems
3	Reasonably precise physics, boundary conditions and geometry **	Simulations with proven convergence, conservation and grid independence	Qualitative agreement of relevant measures for one representative problem **
4	Reasonably precise physics, completely precise boundary conditions and as-built geometry	Fire and Forget (95%+) simulations with convergence, conservation and grid independence **	Qualitative agreement of relevant measures over parametric space of actual problems
5	Completely precise physics, completely precise boundary conditions and as-built geometry	Fire and Forget (95%+) simulations with convergence, conservation and grid independence plus the ability to complete 100 or more problems within 3 weeks	Quantitative agreement of relevant measures over parametric space of actual problem

** Minimum level for significant design impact

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Combustion Devices

- Focus of groups combustion devices activities has been the staged combustion injector technology (SCIT) task
 - Task objective is to develop, validate, and verify a CFD based injector design process
 - Develop required CFD capabilities for supporting large design parametrics
 - Robustness, physical models, turnaround time
 - Generate validation data sets
 - Gas-gas, liquid-gas, liquid-liquid, H₂-O₂, HC-O₂
 - Verify by testing injector designed using new process
- Result of relevance review by Code T is to narrow the focus of the task
 - Program priority will change to advancing design concepts, with CFD capability advancement being secondary
 - Focus on H₂-O₂ injectors, chamber compatibility for expander engines
 - Initial approval for continuation for 3 years

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Combustion Devices - SCIT Continued

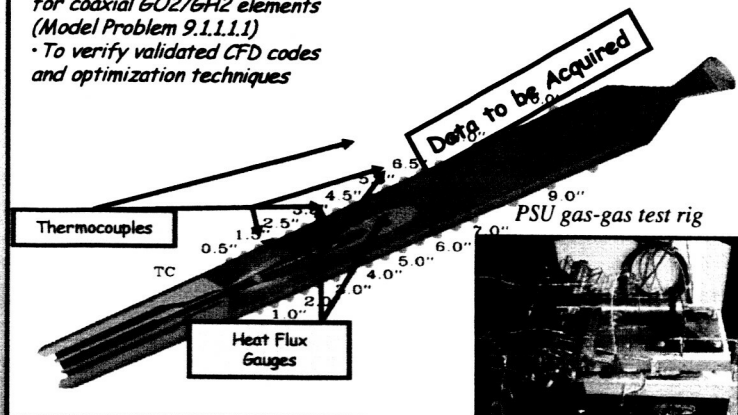


Validation Data Acquisition--GO₂/GH₂ at Penn State

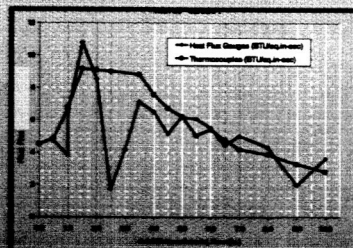
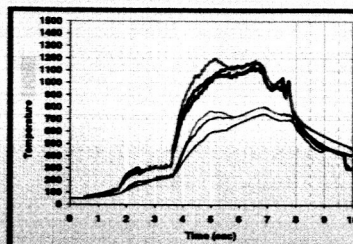
- Have tested initial gas-gas elements at PSU (code validation)
- Initial CFD comparisons have been completed
- Additional testing to focus on advance concepts
 - Probably gas-liquid injectors

OBJECTIVE

- To acquire data to validate codes for coaxial GO₂/GH₂ elements (Model Problem 9.1.1.1.1)
- To verify validated CFD codes and optimization techniques



PSU gas-gas test rig test data



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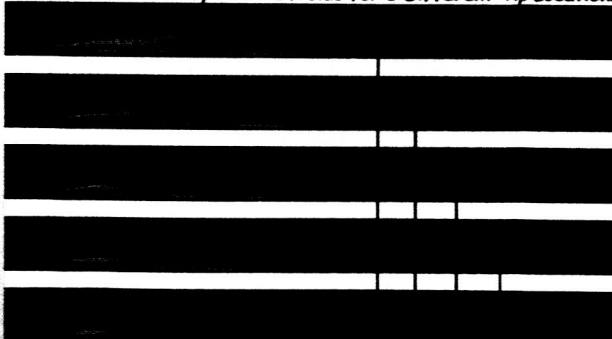
Combustion Devices - SCIT Continued



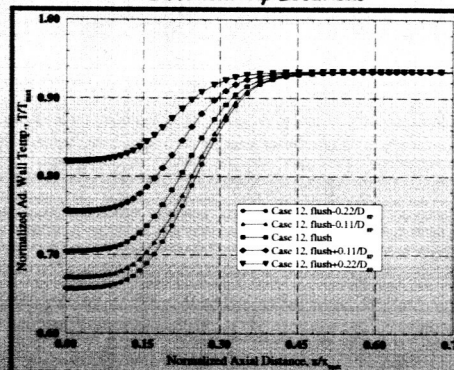
CFD used extensively in concert with PSU testing

- Oxidizer tip location study demonstrates importance of pre-test simulations
 - Also shows knowledge of tip location to be critical
- Application of CFD reinforced need for detail data uncertainty analyses

Pre-Test CFD Temperature Fields for 5 Different Tip Locations

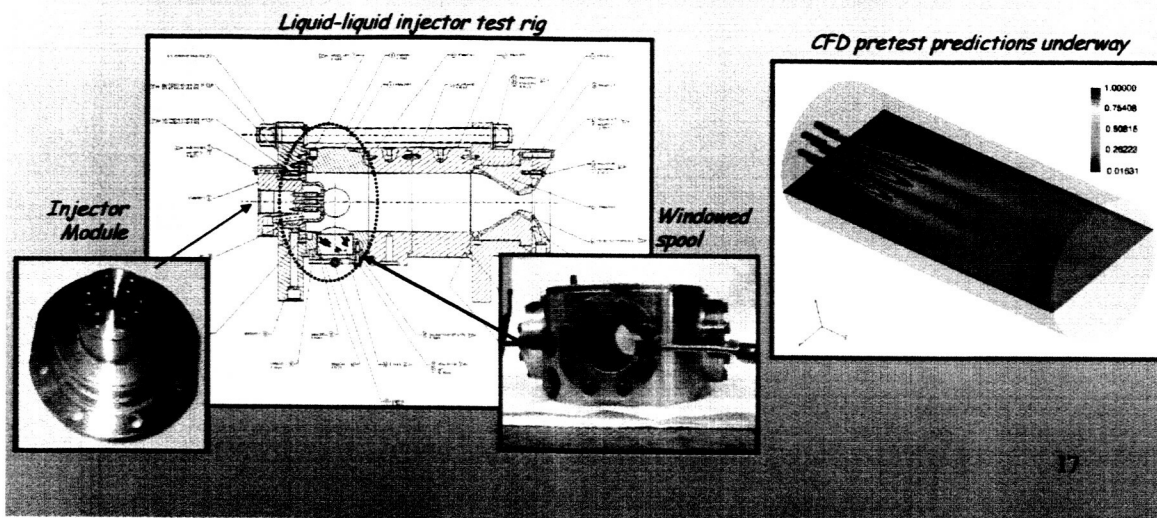


Wall Temperature Profiles for 5 Different Tip Locations



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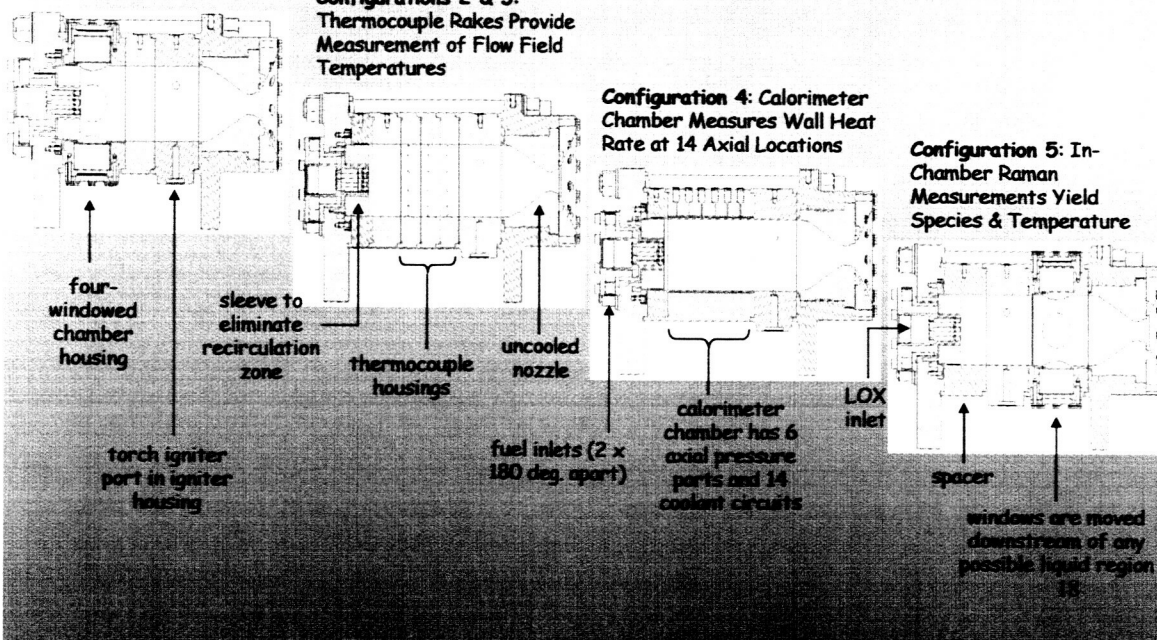
- **Liquid-liquid injector testing at facility TS-115**
 - 7-element, shear coax, LH2-LOX, preburner conditions
 - Testing is underway and data is being reviewed
 - Attempts to obtain multi-element CFD simulations have been hampered by several issues, most notably cpu time required to develop solutions



Configuration 1:
Shadowgraph Imaging of
Propellant Injection Region
& Flame Front

Configurations 2 & 3:
Thermocouple Rakes Provide
Measurement of Flow Field
Temperatures

*These layouts assume that the igniter spool can be
placed far downstream; this remains to be
demonstrated...*





Combustion Devices - SCIT Code Improvement



- Under SCIT there have been several parallel efforts for code improvement
 - FDNS real fluids development and implementation
 - FDNS robustness and efficiency improvements
 - Chenoweth presentation to discuss in more detail
- Development of LOCI-Chem for reacting flows applications (MSU)
 - Density based, generalized grid capability
 - Developed within multi-disciplinary framework
 - Ed Luke presentation
- Development of LOCI-Stream (UF and Stream Numerics)
 - Pressure based code within LOCI
 - Jeff Wright presentation
- All Three codes undergoing nearly constant validation against suite of test cases

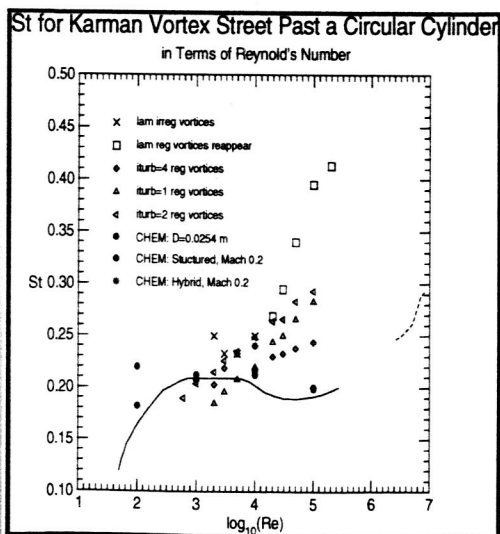
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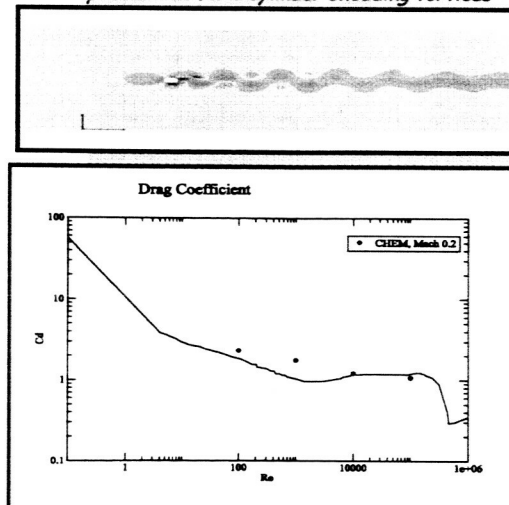
Combustion Devices - SCIT Code Improvement



- Example: Initial validation of LOCI-Chem unsteady capabilities validated against classic vortex shedding cylinder
 - Validation performed by Bryan Robles (new-hire) as part of familiarization w/Chem
 - Results are pretty good but show dependency with Mach number



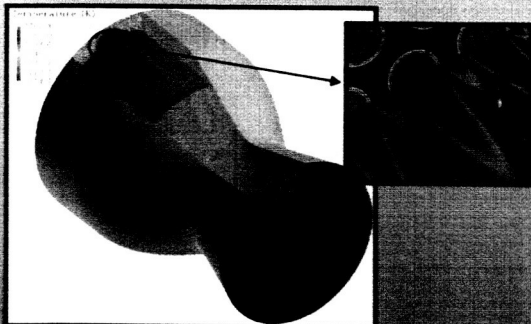
Chem predictions for a cylinder shedding vortices



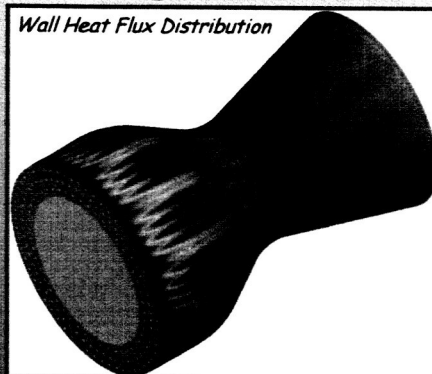
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- **Objective:**
 - Construct a model to evaluate Main Injector and Chamber Wall Environments
 - IPD utilizes (hot) gas-gas H₂-O₂ main injector
- **Approach is to build on experience with PSU gas-gas injector analyses**
 - Apply Chem's capabilities to basically a (large) reacting ideal gas problem
 - "Smart" modeling of the multi-element configuration

Initial IPD multi-element simulation

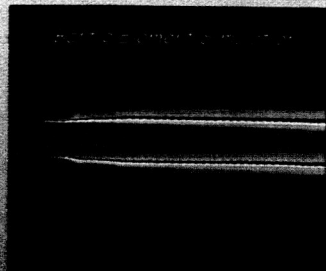
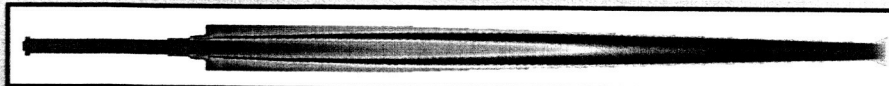


Wall Heat Flux Distribution

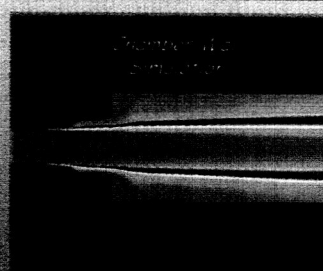


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- **OBJECTIVE**
 - Mitigate design risk by better characterization of thermal environments on baffle elements and on chamber wall
- **APPROACH**
 - Start with Single Element, axisymmetric geometry
 - Finite rate multi-step chemistry, RP-1 modeled as ideal gas
 - Evaluated different GOX injection schemes
 - Evaluated different turbulence models



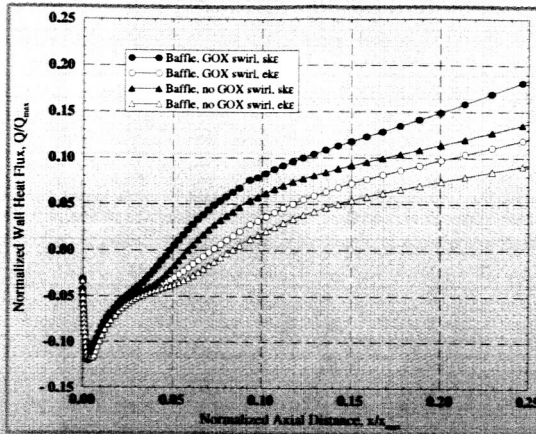
Axisymmetric simulations of an equivalent baffle (mid-chamber) element and a near wall element were performed



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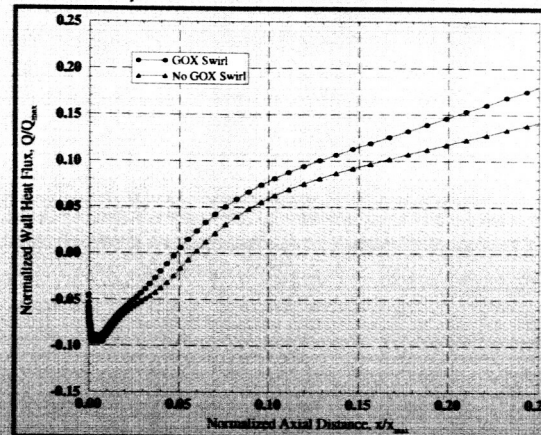
- Example results:

Impact of Turbulence Model on RS-84 Heat Flux



Spread between GOX swirl & no GOX swirl is the same order as between the standard ke and extended ke models

Impact of GOX swirl RS-84 Heat Flux



GOX swirl promotes mixing, thus increasing the near-injector wall heat flux

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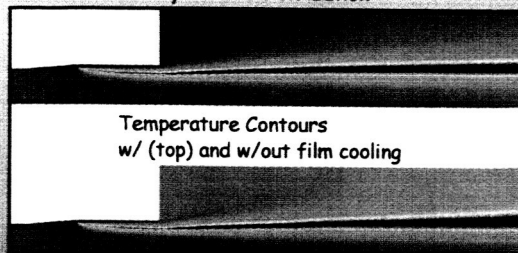
- **OBJECTIVE**

- Construct subscale models to be validated for simulation of large scale combustors
- Use these models to evaluate thermal environments

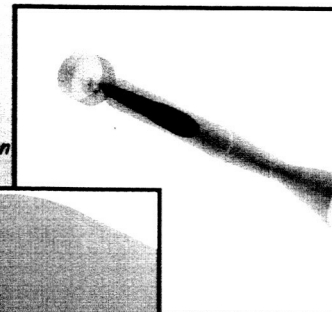
- **APPROACH**

- Start with Single Element, axisymmetric geometry
- RP-1 modeled as ideal gas
- Finite rate multi-step chemistry

Effect of RP-1 film cooling on temperature distribution



Flame front iso-surface on 3D injector simulation



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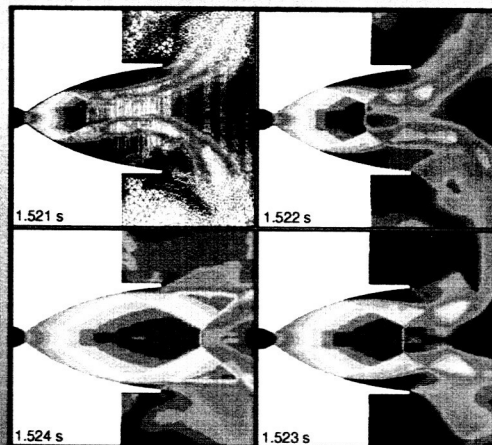
Nozzle Activities



- **Recent/Ongoing Nozzle Technology Activities**

- Documentation of test and analysis results from recent altitude compensation nozzle activities continues
- Nozzle Sideload activity approved for FY04
 - Delayed one year due to Columbia investigation support
- Task to include:
 - Development of CFD based nozzle sideload prediction approach
 - Development of experimental sideload measurement approach
 - Testing of different bell nozzle designs in with air

2D nozzle start-up simulation



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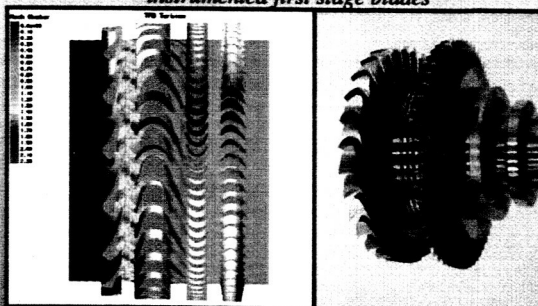


Turbomachinery Activities - TPO



- **Turbopump optimization task**
 - 2 stage supersonic turbine, instrumented rotor
 - Tool improvements, design process improvements, rig design, manufacture, and testing
 - First entry testing completed in Feb 2003, preparing for second entry into facility
 - Test data has been used to make improvements to meanline code
 - Comparisons of Corsair results are very encouraging

*Optimized 2 stage supersonic turbine w/
instrumented first stage blades*



TPO test team



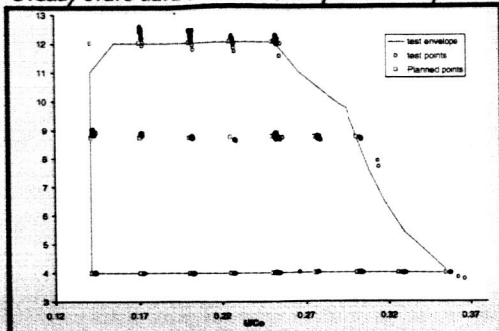
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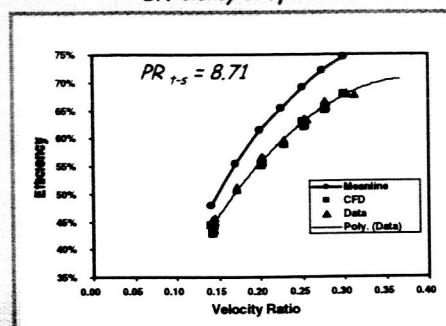
Turbomachinery Activities - TPO



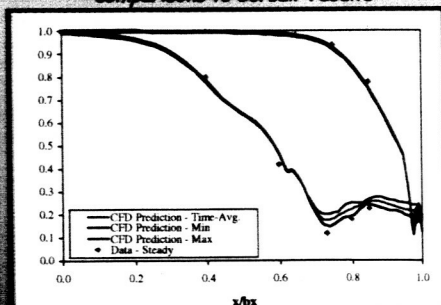
Steady state data obtained at all planned set points



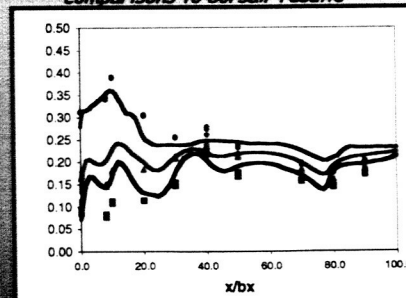
Efficiency comparisons



Nozzle pressure distributions comparisons to Corsair results



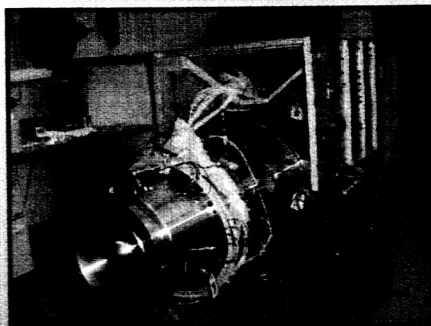
Blade suction side pressure distributions comparisons to Corsair results



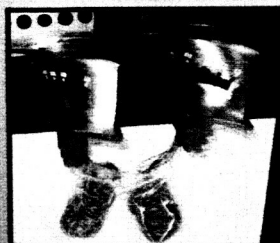
Turbomachinery Activities - TAFT



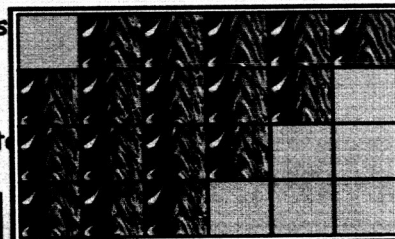
- TAFT - Turbine AirFlow Tester
- RS-84 turbine airflow test rig
 - Subsonic, high flow turbine, out of U.S. industry
 - Design, analysis, manufacture, testing
 - Instrumented rotor for code validation
 - Testing completed, initial comparisons to data



Test rig installed in facility, initial test runs completed



Instrumented blades & nozzles w/ high freq. p measurements



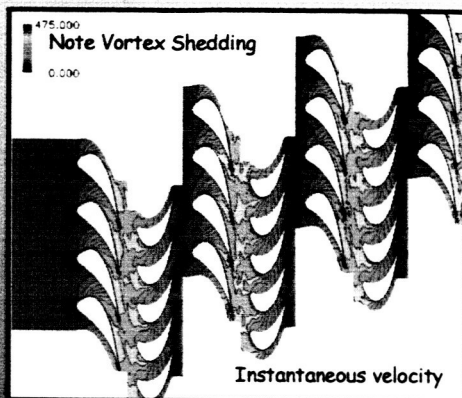
Pretest unsteady CFD analysis of key test points completed

- Performed CFD analyses of the RS-84 LPOT

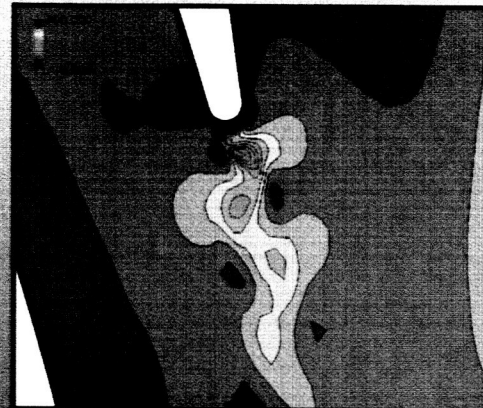
- 6-stage hydraulic turbine
- Analyzed with Phantom (unsteady, real LOX properties)
- Provide steady and unsteady loads, provide insight into unsteady flows
 - Vortex shedding, boundary layer separation, etc.
- Provide performance predictions

Head rise, suction performance, and stationary p' data

2D results for LPOT, first 3 stages shown



Instantaneous velocity at the trailing edge of vane 2 (ft/sec)

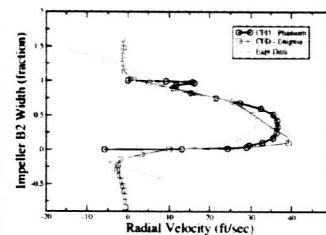


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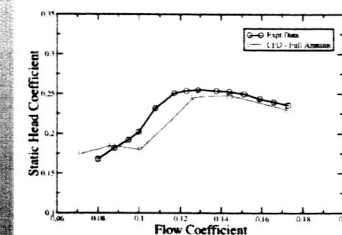
- Task to develop deep throttling diffuse concepts was not selected for continuation

- Task included development of advanced pump diffuser concepts
 - Not completed
- Task also included development of validation database and validation of codes - task was completed
- Phantom (MSFC), Enigma (Rkdn), and INS3D (Ames) validated against experimental data set

*CFD predictions comparison with test data
Impeller exit radial velocity profile*



Diffuser pressure recovery at various Q/N



Experimental pump stage geometry and sample, time-averaged result



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Shuttle Return to Flight



- As part of the Shuttle return to flight activities all the elements are attempting to address areas of concern
 - Even if not related to the Columbia mishap
- CFD is being utilized at MSFC in several areas in support of returning the shuttle to flight
 - External tank (ET) redesign
 - Solid rocket booster separation motors igniter
 - Orbiter fuel feedline liner cracking (again)
 - Shuttle on-pad debris transport process
- Other shuttle support
 - SSME LPOT potential redesign assessment

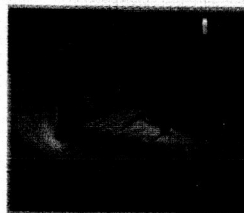
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Shuttle Return to Flight - ET support



- CFD has been heavily utilized in the redesign of the bipod ramp on the external tank
 - Foam loss from the ET bipod ramp led to Columbia mishap
 - CFD used to assess the various redesign candidates
 - CFD utilized heavily in support of the testing of the redesigns
 - Key to designing the test plan
 - MSFC utilized LOCI-Chem exclusively for this work
 - D'Agostino presentation

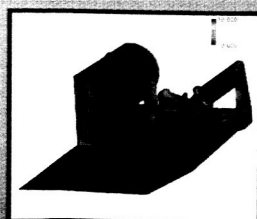


Columbia ET bipod ramp configuration

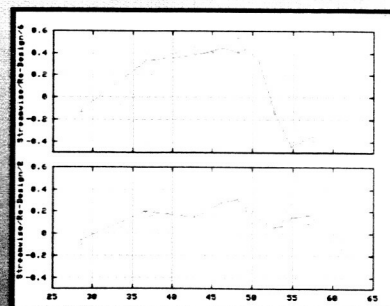


Redesign ET bipod ramp region

Chem comparisons to wind-tunnel data are excellent



Views of the 2 redesigned bipod ET connections



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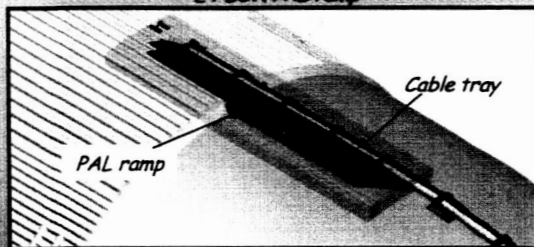


Shuttle Return to Flight - ET support

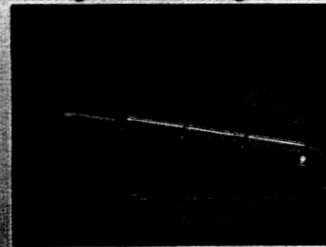


- Currently supporting project office assessing redesign of PAL ramps
 - There are two large ramps that shield the cable trays on the exterior of the ET
 - MSFC performing shuttle stack simulations with overflow to generate flight environments
 - CFD predicted flight environment used to design ground tests of potential redesigns
 - CFD also used to understand results from ground tests
 - In this and other Shuttle RTF activities there has been excellent cooperation in the CFD arena between MSFC, JSC, ARC, and LaRC
 - Reed presentation

ET LOX PAL ramp



AEDC ground test configuration



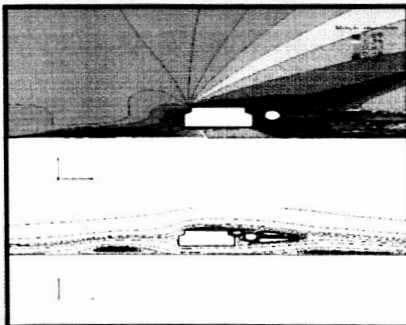
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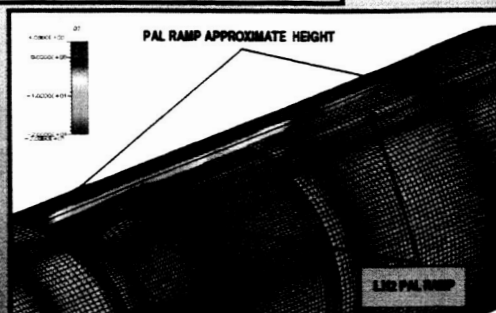
Shuttle Return to Flight - ET support



2D CFD analyses of cable tray and repress line at $M = 0.70$
Flow field unsteady, vortex shedding



Possible solution involves addition of "fence" under the trailing edge of the cable tray to stabilize the flow



Complex, 3D local flow (flow in vicinity of the PAL ramps) make simulation in wind tunnel nearly impossible.

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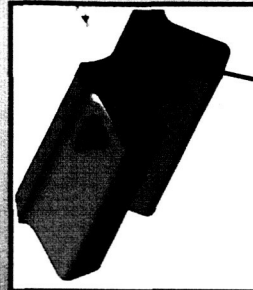
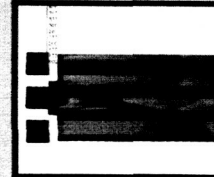
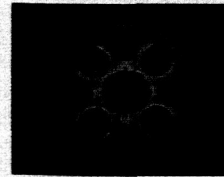


Shuttle Return to Flight - SRB support

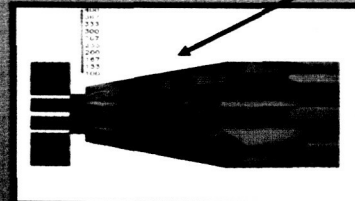


- **Boost separation motors ignition must occur over a very narrow time band in order to separate solid rocket motors from ET safely**
 - Erratic behavior in ground test units traced to potential igniter grain cracking during ignition
 - Structural analysis using CFD results pinpointed failure mechanism
 - Lifting of the igniter bond line due to excessive flow induced loads
- **Testing utilized to assess redesign concepts**
 - CFD used to provide insight into flow induced loads
 - Several limitations in CFD code prevented delivery of quantitative results
 - CFD results used for relative comparisons

Baseline BSM igniter
4-hole, no bevel



CFD loads applied to structural model
predicted failure of bondline



Redesigned igniter
has much lower loads

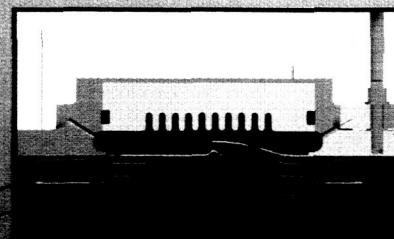
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Orbiter fuel feedline liner cracking



- Orbiter fuel feedline liner cracking caused a grounding of the fleet approximately one year prior to Columbia mishap
- A second look after the mishap has led to re-opening of the investigation to assure that the flow liner will survive at least one mission in the event of an engine out abort
- CFD is being performed by MSFC, Rkdn, and Ames in support of the ground-test program
 - Goal of the testing is to provide data needed to reduce generous conservatism in life prediction tools
 - Simulations are being performed to support water flow testing, airflow testing, and LH2 testing
- **CFD simulation that include cavitation is most useful**
 - Cavitation model being added to Phantom
 - Craft to perform some cavitating simulations



Liner on airflow test article

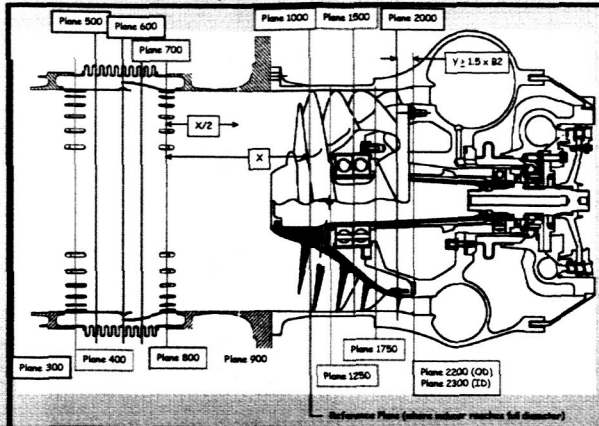
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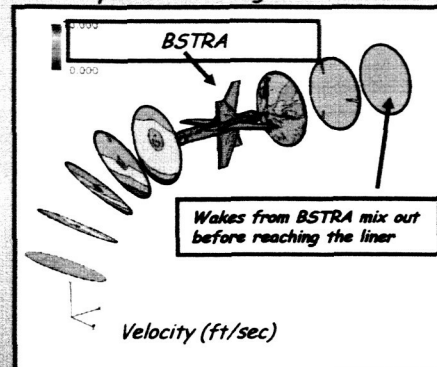
Orbiter fuel feedline liner cracking



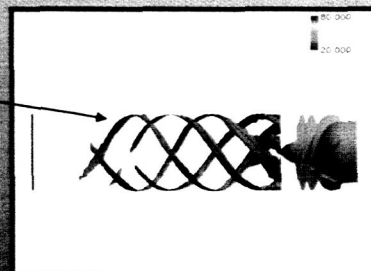
Heavily instrumented air and water test rigs will provide a wealth of data



Initial results with Phantom (real fluids) show that the wakes from the BSTRA do not persist to the engine interface



Axial velocity—5 ft/sec iso-surface colored by pressure (psig)



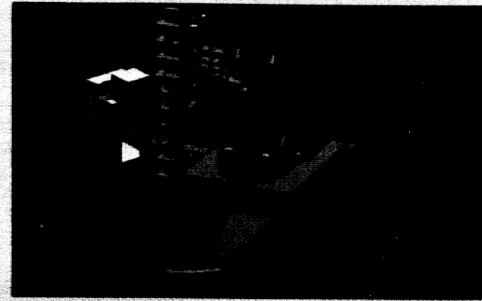
Shuttle Return to Flight - Debris Transport



- Prior to returning to flight, NASA committed to having in place a discipline process for dealing with debris during a mission
 - All the shuttle elements are generating list of possible debris
 - The potential for that debris to cause damage to the shuttle system is evaluated in a two parts process
 - Debris transport and debris impact
 - Impact testing of key components is being used to determine what is the allowable debris
- CFD is being utilized heavily in the debris transport process
 - Overflow is used to calculate the flow field about the shuttle at specified flight conditions
 - The trajectory that a specific piece of debris will follow is then calculated using a decoupled code
 - As necessary, coupled 6-DOF simulations of debris and shuttle are performed
- JSC has responsibility for the "ascent" debris transport
- MSFC is responsible for the "on-pad" debris transport
- There is a strong incentive for utilizing the same codes at MSFC and at JSC.

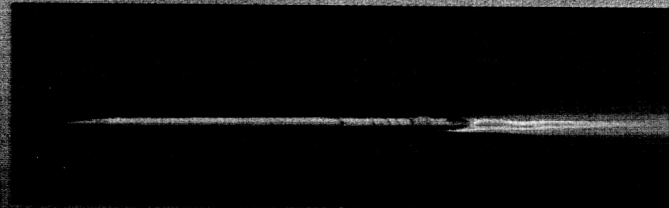


- There are several risks associated with performing the "on-pad" debris transport calculation
 - Risk that Overflow will not predict the on-pad flow fields
 - Flows dominated by plume induced aspiration
 - Risk that the complex geometry of the launch pad/shuttle stack may make the grid generation impractical and/or lead to unacceptable solution run times
 - West presentation



Initial capability is to include shuttle stack and mobile launch platform

Solid rocket booster alone model for low-mach # Overflow testing

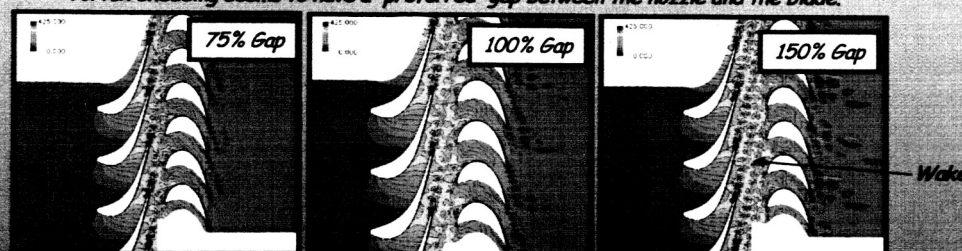


SSME LPOT potential redesign assessment



- **Current SSME LPOT has experienced cracking of the 1st stage nozzle**
 - Caused by coupling between vortices shedding and structural mode
 - After extended test time exposure
- **The project has requested that potential redesigns that eliminate the potential for nozzle failure be developed.**
 - MSFC has supported Rocketdyne and Ames with CFD analyses of the baseline design and potential redesigns
 - Dorney/Marcu presentation

Vortex shedding seems to have a "preferred" gap between the nozzle and the blade.



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Concluding Remarks



- **TD64 focused on supporting the space transportation programs**
 - Shuttle return to flight
 - Applying capabilities/technologies to Office of Exploration System needs
- **Design and analysis tools being applied and/or under development in the major hardware areas**
 - Turbines, pumps, combustion devices, engine systems, propulsion-to-airframe integration, and MDA capabilities continuously being improved
- **Increasing the design process efficiency and fidelity is paramount**
- **Code validation, robustness, reliability key to meeting CFD's promise**
- **Achieving goals depends on our ability to get maximum return on research investments**